Implementation of Specific Displacement Diagrams for the Control of Kinetic Sculptures with Yaskawa Electronic Cams

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Abstract Electronic cams are used for different manufacturing systems, but in terms of displacement diagrams, they have common characteristics. The emphasis is usually placed on maximum accuracy, the machine cycle time and the displacement diagram has a simple shape. This paper addresses a completely different case, which shows that the use of electronic cams is very diverse. A Yaskawa's electronic cam was used to control the kinetic art sculptures. It was necessary to develop an implementation that will be able to accommodate a large number of very long and complex displacement diagrams. Sculptures contained up to 150 interpolating axes and their programs took up to half an hour. The proposal builds on the basic animation and designer's demands, but it must comply with all limits of the mechanism (maximum speed, torque, etc.). The classic electronic cam uses a data table and interpolation function. This approach has been replaced with a new feature that composes the movement from polynomial of the 5th order. For this purpose, it was developed an independent software tool. The final displacement diagram is composed by defining the 0th, 1st, and 2nd derivatives at the key points. This method of design has proved to be very effective, and in addition, this implementation brought a significant saving of memory and reducing of computational complexity.

Keywords Electronic cam · Displacement diagram · Polynomial function

1 Introduction

For production systems, displacement diagrams are usually supplied by the contracting authority or generated by specialized software tools (in VÚTS, we use our own tools KINZ and KINZ2 [1]). Displacement diagrams (Fig. 1) can be composed

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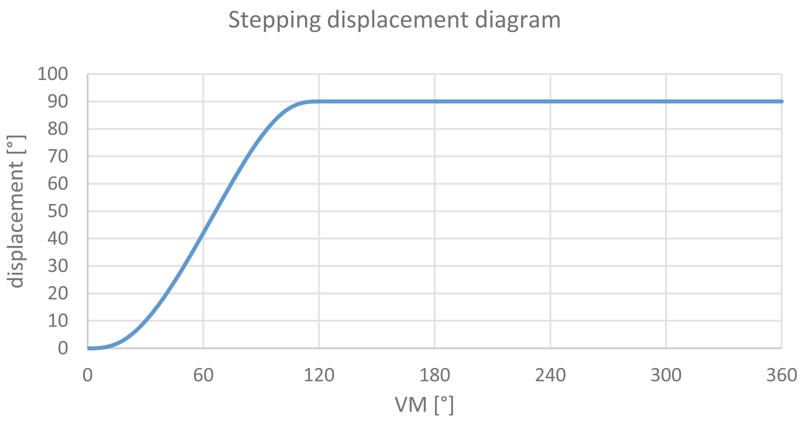

Fig. 1 Displacement diagram used e.g. for rotary table

from different functions (higher order polynomials, trigonometric functions, exponential, and combinations thereof). In the PLC (Programmable Logic Controller), data are stored in a table where the first column contains the coordinates of independent variables, i.e. the virtual master (hereinafter referred to as VM). The second column represents rotation of the output shaft of the motor. The next columns contain higher derivatives which are used to improve the regulatory process. A step of the VM can be constant or variable.

In the system of Yaskawa electronic cam, it is for proper operation necessary to know the values of displacement for any rotation of VM. It uses the internal FGN function that implements binary search in the field of input data and then linear interpolation between the nearest points.

Based on the contract for the controlling of kinetic sculpture [3], it was necessary to revise the above approach. Displacement diagrams were supplied in the form of data, but it cannot be directly used for the electronic cam. Data were created in graphic software tools, so they did not apply continuity of higher derivatives (velocity and acceleration) and they did not take into account the physical limits of the mechanism (maximum speed, etc.). In total, there were up to 75 servo motors controlled by one PLC and the whole scene lasted nearly half an hour. The approach used for production machinery would exceed the computational and memory capabilities of the PLC.

2 Division on Polynomials

The displacement diagram was divided into sections which were replaced with individual functions. As a general replacement, it was chosen to the 5th degree polynomial. The function is determined by conventional notation [2].

$$y = c_5x^5 + c_4x^4 + c_3x^3 + c_2x^2 + c_1x + c_0 \tag{1}$$

For implementation in the control system, it is used notation according to Horner scheme.

$$y = ((((c_5x + c_4)x + c_3)x + c_2)x + c_1)x + c_0 \tag{2}$$

This implementation guarantees the most effective method of calculation. It used only 5 additions and 5 multiplications, the computational complexity in the control system is lower than, for example, calculation of the sine function.

The 5th degree polynomial can also be very intuitive and easy to define using the boundary conditions. Practically, it is about to enter the 0th, 1st and 2nd derivatives at the endpoints. Sharing these points between the adjacent functions ensures the continuous shape resulting displacement diagram, including the first two derivatives. Calculation of individual coefficients using the boundary conditions is demonstrated by the following relations (3) to (8), where boundary points are labeled 0 and 1.

$$c_0 = y(0) \tag{3}$$

$$c_1 = y(0)' \tag{4}$$

$$c_2 = \frac{y(0)''}{2} \tag{5}$$

$$c_3 = \frac{1}{2(x(1) - x(0))}\left(20\frac{y(1) - y(0)}{(x(1) - x(0))^2} - 4\frac{2y(1)' + 3y(0)'}{x(1) - x(0)} + y(1)'' - 3y(0)''\right) \tag{6}$$

$$c_4 = \frac{1}{2(x(1) - x(0))^2}\left(-30\frac{y(1) - y(0)}{(x(1) - x(0))^2} + 2\frac{7y(1)' + 8y(0)'}{x(1) - x(0)} - 2y(1)'' + 3y(0)''\right) \tag{7}$$

$$c_5 = \frac{1}{2(x(1) - x(0))^3}\left(12\frac{y(1) - y(0)}{(x(1) - x(0))^2} - 6\frac{y(1)' + y(0)'}{x(1) - x(0)} + y(1)'' - y(0)''\right) \tag{8}$$

A specific example composition of displacement diagrams from two polynomials is shown in Fig. 2, which was captured directly from the applications developed for the design of displacement diagrams.

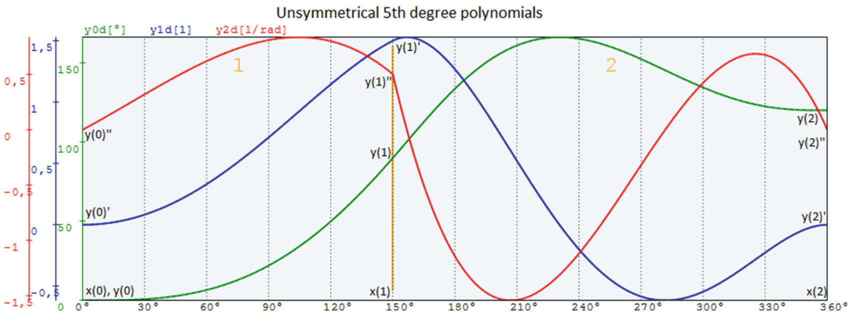

Fig. 2 Creating of displacement diagram by folding polynomials

3 Implementation in the Control System

Based on the data from the customer's animation software, physically realizable displacement diagrams were created by specialized software tools. Curves are usually made up of many functions (in some cases up to 60 functions) of the 5th order polynomial. The software tool also implements a library with a Modbus TCP communication protocol, which allows direct communication with the PLC, as shown in Fig. 3. Displacement diagrams or more precisely parameters of functions are directly transmitted as data frames, stored in a predefined format (see Fig. 4) into the PLC memory. For a definition of one polynomial, there are necessary seven coefficients (*x*-coordinate of the end point and 6 polynomial coefficients).

The control program in the PLC in the first step (before starting the electronic cam) searches the currently used polynomial by the position of the VM. Subsequently, displacement is calculated according to (2) until the interval of the current polynomial is exceeded. Due to the length of polynomials and the step size of the VM, we can safely assume that we always change no more than one polynomial.

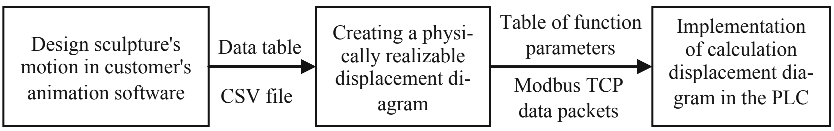

Fig. 3 Data flow diagram in the creating of displacement diagram

Polynomial 0							Polynomial 1							…
x_1	c_{00}	c_{01}	c_{02}	c_{03}	c_{04}	c_{05}	x_2	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	…

Fig. 4 Transmitted data frame

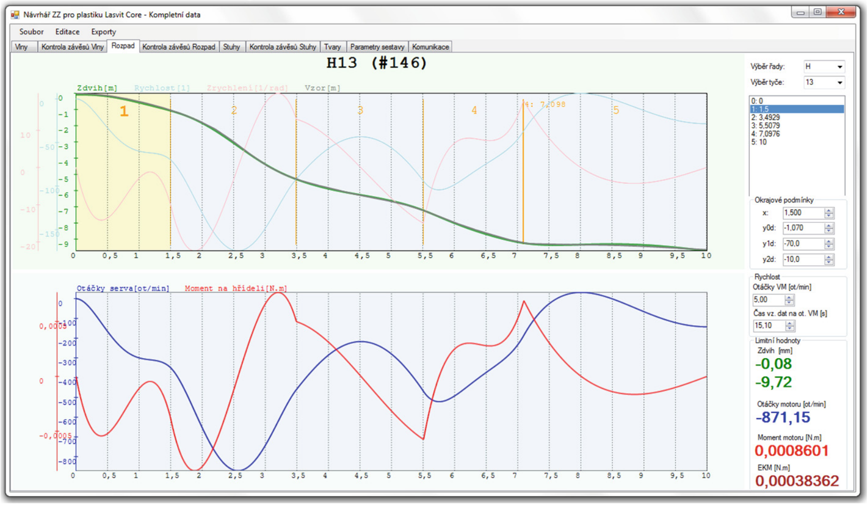

Fig. 5 Practical demonstration creating of displacement diagram (*green* stroke, *blue* motor speed, *red* motor shaft torque) (Color figure online)

Consider the already mentioned situation when we want to control the 75 drives. The displacement diagram has a shape as shown in Fig. 5 and it is replaced by 5 polynomials. If we calculate similar complexity also for other axes, we can estimate the overall memory demands according to the following relation (9) to the 2625 coefficients.

$$\text{num. of coeff.} = 7 \times \text{num. of polynomials for displacement diagram} \\ \times \text{num. of controlled axes} \quad (9)$$

Although the reduction of memory demands is clear, we cannot objectively compare these numbers because it is always an approximation of the original displacement diagrams. Determining when it is a sufficient approximation and when not is always subjective, especially in this case when the aim is the artistic impression rather than accuracy.

4 Conclusion

The realization of kinetic sculptures brought completely new requirements for implementation of displacement diagrams. In place of a simple but strictly defined displacement diagram, it was necessary to effectively implement complex movements whose purpose is not to create a product, but the artistic impression.

At first, the developed method divided the displacement diagram to individual sections which are replaced by the 5th order polynomial. This approximation is sufficient to preserve the character of the movement and also very efficient from a technical perspective. The displacement diagram keeps continuity to the second derivative (acceleration) and its memory and computational requirements are relatively small.

The practical outcome is a graphical software tool for a rapid assembly of a displacement diagram based on data from the customer graphical tool. It also implements a communication library for the direct memory access to control the system of electronic cams which realized calculation of displacement. Everything has been practically applied in the implementation of two kinetic sculptures and is ready for use in other similar systems.

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